

IMPLANT DESIGN INFLUENCING IMPLANT SUCCESS: A REVIEW

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ABSTRACT

During dental implant treatment-planning, stress transfer at implant-bone interface is a critical factor which depends upon macroscopic and microscopic implant features. Many engineering studies have shown that implant shape, thread design and surface characteristics influence the extent of bonding between bone and implant. In addition, implant design should also be considered since affects basic bone physiology processes regarding bone modeling/remodeling and bone's stimulation.

KEYWORDS: Implant Design, Implant Thread, Bone Stimulation, Wolf's Law, Surface Characteristics

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INTRODUCTION

In the early stages of implant dentistry, root implants or endosseous implants were found to be better than many other different types of implants used since they could provide higher success rates and lower patient discomfort. Thereafter, implants are available in various designs such as tapered, cylindrical, and press-fit or a combination of these features.^[1] Other features of the implants' design to consider are thread shape, thread pitch, thread depth and implant neck design (**Figure 1**). Dental implant's apical design, its diameter, and length in relation to available bone also play an important role. The aim of this review is to provide the implant success osseointegration rationale influenced by implant design factors.

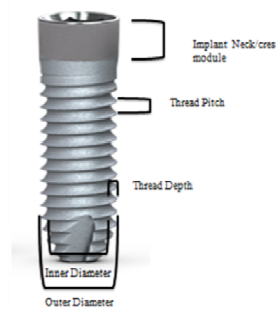


Figure 1: Basic Implant Design

Bone Stimulation

The main focus of any implant design is to improve surgical success rate and reduce plaque-related complication after treatment. Surgical success rate can only be achieved when proper osseointegration takes place. The rationale behind macro- and micro-features in implant design is that the bone is stronger when loaded in compression, contrary to when subjected to tensile force and loaded in shear. Thus, when an implant is placed, it should be attempted to increasing the compressive force exerted.^[1,2] This is based on Wolff's law which states that "nature economizes on bone and tends to dispose of bone that is not optimally used".^[3] Therefore, a dental implant should be designed to stimulate bone adequately since over stressing the implant would reabsorb the bone.

Dental implant design must fulfill these operational criteria to be successful:^[1]

- Gain initial stability that reduces micromotion and the waiting-period for loading the implant.
- Diminish the effect of shear forces on the interface to preserve marginal bone.
- Design features that stimulate bone formation and/or facilitate bone healing.

Implant Shape

An implant can be tapered or threaded cylindrical or smooth cylindrical. Cylindrical implants can be placed in anterior and posterior teeth regions but tapered only in anterior region. Smooth-sided cylindrical implants provide ease in implant placement; however, they provide greater shear conditions. In contrast, smooth-sided tapered implants provide compressive force on the bone-implant interface, depending upon the taper. The greater the taper, the greater is the component of compressive force. The amount of taper should not be more than 30 degrees or the implant body length should be significantly reduced along with the immediate fixation required for the initial healing.^[1] Unlike a cylinder implant, a tapered threaded implant bear the compressive loads to the bone providing no functional surface area advantage. A smooth-surfaced cylindrical implant results in shear load on the bone and this type of implant must rely on the microscopic feature such as mechanical etch for better bone-to-implant contact (BIC).^[1]

IMPLANT THREAD

Threads have been incorporated into implants to improve initial stability^[4, 5] enlarge implant surface area, and distribute stress favorably.^[6,7] Kohn et al^[8] demonstrated the presence of a bone-bridge from the depth of one thread to another, when the implants were laterally loaded and concluded that strain is more concentrated in the area where bone contacts the crest of the thread and the strain decreased from the crest to the root of the thread. It has been proposed that

threads, due to their uneven contour will generate a heterogeneous stress field, which will match the ‘physiologic overload zone’, thus prompting new bone formation^[9] which may support the ‘cuplike bone formation’ at the crest of the implant thread.

- **Thread Shape**

Thread shape is determined by the thread thickness and thread face angle.^[2] The thread shape of an implant have the ability to convert occlusal loads into more favorable compressive load at the bone-implant interface. Presently, there are five basic thread shapes available² (**Figure 2**).

Under axial loads to an implant-bone interface, a buttress or a square shaped thread would transmit compressive force to the bone. V-shape and the broader square shape generated significantly less stress compared with the thin and narrower square thread in cancellous bone. However, cortical bone showed no difference among threads.^[2] Thus, both thread designs are more favorable configurations for dental implants especially when dealing with cancellous bone.^[10, 11] When not loaded, bone density is equally distributed above and below the thread, whereas when under dynamic loading, bone density is higher below the threads and wear only on the threads’ tip.^[12-14]

Knefel^[15] investigated five different thread profiles, and found the most favorable stress distribution to be demonstrated by an ‘asymmetric thread’, the profile of which varied along the length of an implant. Misch et al^[1] suggested that “v”-shape (30° angle) generate higher shear force than reverse buttress thread (15° angle). Both types of threads have been shown to generate forces which may lead to defect formation.^[16]

The axial load of squared and buttress threads are mostly dissipated through compressive force,^[17,18] while v-shaped and reverse buttress-threaded implants transmit axial force through a combination of compressive, tensile and shear forces.^[1] In an animal study conducted by Steigenga et al,^[19] square thread implants were found to have greater BIC and higher reverse torque when compared with v-shaped and reverse buttress implants.

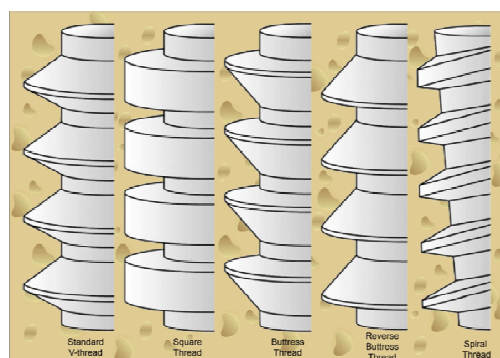


Figure 2: Basic Thread Designs

- **Thread Pitch**

The thread pitch is the distance from the center of the thread to the center of the next thread, measured parallel to the axis of a screw. The fact that thread pitch has a greater effect on surface area within a small dimensional range which may be used to help resist the forces to bone with poorer quality makes it an important feature.^[20] For a v-shaped thread, pitch is defined as the distance between the adjacent threads; for a square-shaped thread it is the distance between the two thread features. The smaller the pitch, the more threads are present on the implant. A disadvantage of a smaller pitch is the greater number of revolutions required to place the implant in the surgical site.^[20] Kong et al^[21] considered 0.8mm as the

optimal thread pitch for achieving primary stability and optimum stress production on cylindrical implants with V-shaped threads. The authors also stated that stresses are more sensitive to thread pitch in cancellous bone than in cortical bone.

Thread pitch differs from thread lead, which is the distance from the center of the thread to the center of the same thread after one turn or, more accurately, the distance that a screw would advance in the axial direction if turned one complete revolution.^[2] The lead basically determines the speed in which an implant will be placed in bone, if all other conditions are equal (e.g., pitch distance). In a single-threaded screw, lead is equal to pitch, however in a double threaded screw, lead is double the pitch and in a triple-threaded lead is triple the pitch.^[2] An implant with double threads would be inserted twice as fast than the single threaded, and the triple threaded would only need a third of the required time for a single-threaded. This means that when one thread lead implant rotates 1 rpm, the implant inserts a distance of one thread.^[1] Thread lead do not increase the surface area but is a manufacturing process in which rather than machining one thread at a time with one cutting instrument, a double thread uses two cutting blades and a triple thread uses three blades to manufacture the threads.^[1]

- **Thread Depth**

The thread depth is the distance between the major and minor diameter of the thread. A straight minor diameter results in uniform cross-sectional area throughout the cylindrical implant.^[1] However, in a tapered implant the outer diameter decreases at the apical end and so the thread depth, resulting in a decreased surface area which is critical in shorter implant length.^[1] Thus, the greater the thread depth, the greater the surface area of an implant if all other factors are equal. The more shallow the thread depth, the easier it is to thread an implant in a dense bone.^[1]

In a commercially available implant system characterized by progressive threads (e.g., Ankylos, Dentsply Friadent), the threads have higher depth in the apical portion and then decrease gradually coronally.^[2] This design might increase the load transfer to the more flexible cancellous bone instead of crestal cortical bone, and may contribute to less cortical bone resorption.

CREST MODULE

The neck of the implant is called crest module. Ideally, this feature should be slightly larger than the outer diameter of an implant^[1] for the following reasons:

- This is where the implant meets the soft tissue and changes from a virtually sterile environment to an open oral cavity.^[2]
- The seal created by larger neck also provides for a greater initial stability during placement, especially in a softer unprepared bone as it compresses the crestal bone region.^[1]
- Larger neck also increases the surface area.^[1]
- Larger neck increases the platform of the abutment connection with a stress reduction to the abutment screw during lateral loading.^[1]
- According to Bozkaya et al^[22] moderate occlusal loads do not change the compact bone. However, when extreme occlusal loads were applied, overloading occurs near the superior region of the compact bone. Hence, it was concluded that the crestal module may minimize bone stress.

NECK DESIGN: ROUGH OR SMOOTH

Crest module can be smooth or rough. A rough surface favors osseointegration, meaning, crest module with rough surface design should be considered. But if bone loss occurs, rough surface gets exposed to the oral cavity favoring plaque accumulation resulting in further bone loss. Thus, use of a smooth neck on rough implants resulted from the attempt to decrease plaque retention. It has also been suggested that the implant neck should be smooth/polished, supporting the belief that the crest module should not be designed for load bearing.^[23] However, smooth portion increases shear forces resulting in marginal bone loss and eventually more pocket formation.^[24,25] Herrmann et al^[26] compared rough and smooth surface implant necks placed in dog model and after 1 month of loading, marginal bone loss was observed in smooth surface necks of 1.5 mm. The same result was also observed when the study was conducted in humans.

According to Wolff's law^[27] the presence of retentive elements at the implant neck will dissipate some forces leading to the maintenance of the crestal bone height. Schrotenboer et al^[28] found micro-threaded implants increase bone stress at the crestal portion when compared with smooth neck implants. Palmer et al^[29] demonstrated maintenance of marginal bone levels with an implant that had retentive elements at the neck. In another dog model, Abrahamsson & Berglundh^[30] found increased BIC at 10 months in implants with micro-threads in the coronal portion (81.8%) when compared with control non-micro-threaded implants (72.8%). Lee et al^[31] in a human study comparing implants with or without micro-threads at the crestal portion indicated that addition of retentive elements might have an effect in preventing marginal bone loss against loading.

It appears that when the implant heads are placed at the crest, cortical bone will change in the process of establishing a biologic width; this modeling/remodeling behavior occurs to the level where the screw threads start and/or the roughened surface topography begins.^[23,32] The use of a roughened crest module that is at the bone crest level, may provide a positive stress stimulus to the bone and decrease bone loss in this area.^[33] Thus, when an implant with a smooth neck is selected, it should be placed over the bone crest.

IMPLANT SURFACE

It is well-known that titanium implants osseointegrate and evolution in implantology has shown that cell adhesion on rough surface takes place through Filopodia which are Actin rich cell extensions.^[34] Filopodia scan substrate's surface structures and stabilize the cell according to signals received from micro- or submicro-metre-structured pores which act as a favorable environment during the path-finding phase.^[34] On the other hand, cells adhere with smooth surface through focal adhesion. Filopodia while scanning the smooth surface get negative signal and retract back to the cell body, resulting in well developed stress fibers which exert tension across the cell body making more flattened cells with reduced cellular attachment to their surrounding substrate.^[34] In order to achieve better osseointegration, scientists developed second generation implants with surface modifications such as machining, sandblasting, acid etching, anodic oxidation, laser modification or a combination of these.^[35]

- **Machined Surface**

The machined implant surface is considered to be minimally rough; moreover, manufacturing tools, bulk material, lubricant and machining speed will influence the surface topography. The surface oxide consists of a 2-10 nm thick mostly amorphous layer of TiO₂ (titanium oxide)^[36] Depending on the sterilization method the oxide layer could be crystallized into rutile structure.^[37] The healing around the implant is characterized by an increase in bone-implant contact starting at

the implantation while the biomechanical stability slightly decrease over the first weeks, possible due to inflammation and bone remodeling, and being fully recovered after 4 weeks in rat tibia.^[38]

- **Sandblasted Surface**

Sandblasted surface has increased roughness which is achieved by blasting the surface with small particles, usually called sandblasting or grit blasting. The basic concept is that when the particles hit the implant surface they create a crater, thus the roughness depends upon the bulk material, the particle material, the particle size, the particle shape, the particle speed and the density of particles.^[35] Higher bone-implant contact was observed for the 25 μm blasted surface compared to machined surface.^[39] The biological response to blasted implants have shown an optimal bone response to removal torque values and bone implant contact to implants when a roughness of 1.5 μm is achieved.^[40]

- **Acid Etched Surface**

In this type of surface modification, the surface is pitted by removal of grains and grain boundaries of the implant surface, as certain phases and impurities are more sensitive to the etching a selective removal of material is obtained.^[35] The resulting roughness is dependent on the bulk material, the surface microstructure, the acid and the soaking time.^[35] Significantly higher bone implant contact was observed in a poor bone quality dog model after 4 months healing.^[41] Significantly increased removal torque was needed to remove acid etched implants compared to the machined implant after 1, 2 and 3 months healing in rabbit.^[42]

- **Sandblasted and Acid Etched Surface**

A sandblasted and acid etched surface (SLA) is a surface blasted by particles and then etched by acids. This is performed to obtain a dual surface roughness as well as removal of embedded blasting particles.^[35] The etching reduces the highest peaks while smaller pits are created and the average surface roughness becomes reduced.^[35] The chemical process of the acid etching creates a titanium hydride layer on the surface with a thickness of 1-2 μm intermediate the surface oxide and the bulk metal.^[43] Furthermore, SLA implant is rinsed in a nitrogen atmosphere and stored in saline solution until installation, which reduces the amount of carbon contamination and improves the hydrophilicity of the implant surface,^[44] as a result, a new hydrophilic surface (SLActive) is created. This procedure allows the SLActive to maintain a chemically active surface that is conditioned to the human body. According to Ellingsen et al,^[45] higher removal torque and higher bone-implant contact has been observed for blasted and fluoride modified implants compared solely blasted implants in a rabbit model after 1 and 3 months healing. Studies have shown that SLActive implants achieve a higher bone contact and stability at earlier time points (6 weeks) and dramatically reduced healing times from 12 to 6 weeks.^[46]

- **Anodized Surface**

The anodized surface (TiUnite) is partially crystalline and phosphate enriched titanium oxide characterized by a micro structured surface with open pores in the low micrometer range. This oxidization is an electrochemical process carried out in an electrolyte. Also, depending on the electrolyte composition, different ions could be integrated in the oxide layer. Literature has shown significant higher BIC, as well as increased biomechanical removal torque values for phosphorous containing anodized surfaces compared to machined surfaces in dog and rabbit,^[47] also phosphorous containing anodized surface promotes early molecular events taking place at the immediate implant surface.^[48] A higher clinical success rate has been observed for the anodized titanium implants in comparison with turned titanium surfaces of

similar shapes,^[49] and can be attribute due to mechanical interlocking through bone growth in pores, and biochemical bonding.^[50]

- **Laser Modified Micro- and Nano-Structured Surface**

In Laser modified surfaces, complex surface geometries can be produced on the surface, by focusing short pulses of light of single wavelength on one spot. It is rapid, extremely clean, and suitable for the selective modification of surfaces and allows the generation of complex microstructures/features with high resolution,^[35] enabling this technique for geometrically complex biomedical implants. The laser technique has several advantages, such as no chemicals are used in routine manufacturing. Studies of laser-modified titanium implants with nanoscale surface topographical features have demonstrated a significant increase in removal torque and different fracture mechanisms.^[51] Nanostructured surfaces promoted long-term bone bonding and interface strength *in vivo* as determined by coalescence between mineralized bone and the nanostructured surface and a substantial increase in removal torque.^[51]

CONCLUSIONS

Implant success does not depend upon just one factor; it is an accumulation of implant design characteristics which are important in load transfer and maintaining implant success (**Table 1**). Implant selection depends upon case to case, but it should be understood that one sole factor will not account for success and that several other factors might have an effect on the treatment provided.^[2]

Table 1: Implant Design Features and Bone Quality Affecting the Degree of Primary Stability

Increased Primary Stability
Good bone quality
Long implant
Wide diameter implant
More threads
Smaller pitch
Deep threads
Decreased thread helix angle
DECREASED PRIMARY STABILITY
Compromised bone quality
Short implant
Narrow diameter implant
Fewer threads
Longer pitch
Shallow threads
Increased thread helix angle

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